February 8, 2000

Ms. Magalie Roman Salas
Office of the Secretary
Federal Communications Commission
The Portals
445 Twelfth Street, S.W., Room TW-A325
Washington, D.C. 20554

RE: Amendment of Part 15 of the Commission's Rules Regarding Spread Spectrum Devices, ET Docket No. 99-231

Dear Ms. Salas,

Lucent Technologies Inc. (Lucent) submits the following attachment for the Commission's consideration in the above-mentioned proceeding. The attachment is a supplement to the paper *"Interference Potential of WideBand Frequency Hopping Systems on Packet Data Systems,"* Annex 1 of IEEE 802.11-99/239, which was filed by the Local and Metropolitan Area Networks Standards Committee of the Institute of Electrical Engineers (IEEE-LMSC) on October 2, 1999.[1] Annex 1 of IEEE 802.11-99/239 presented a study of the effect of an increase in frequency hopping bandwidth on interference to legacy packet LAN systems, including systems conforming to the LMSC standard and current Commission rules.

This supplemental analysis further supports Lucent's previous comments and reply comments filed in this proceeding, by elaborating on the interference created by wideband frequency hopping (WBFH) systems. It supplements the previous analysis by adding the effect of faster frequency hopping (FH) on legacy systems. Its results are even more realistic than the original IEEE-LMSC paper because we studied wideband interference to legacy system receivers that are more representative of systems currently deployed. Specifically, we analyzed receivers in which the receiver bandwidth is higher than the emission bandwidth. This supplemental analysis is more complete and extensive and includes the effect of an unproductive initialization phase (synchronization, start up transients etc.) on frequency hopping segments.

This supplement shows that wideband fast frequency hopping at multiple hops per victim packet creates more interference than does the single hop per packet rate assumed in the original paper. Very high levels of interference on victim systems result because interference collisions occur at higher rates due to both the wider transmit bandwidth and the higher hopping rate. Fast frequency hopping interference levels are higher than levels predicted in Annex 1 of IEEE 802.11-99/239 because of the limited hop time assumed in Annex 1.

[1] *See* Letter from James T. Carlo to Magalie R. Salas, October 2, 1999.

In addition, the supplement addresses the interference effect of inefficiencies created by faster hopping times. Following a jump to a new frequency, FH systems must allow a fixed length of time to settle filters and reacquire synchronization. During this rest period, the new frequency remains unused. As FH systems employ faster hopping rates, this rest period does not shorten significantly and thus becomes more significant relative to the productive portion of the hop time. This effect ultimately limits the achievable hopping rates. Although the supplement shows that the relative interference effect of the faster hopping rate is lower due to this effect, it is nevertheless significant and higher than that of the limited hopping rate assumption of the original LMSC paper.

In summary, this supplement supports the conclusions of Annex 1 of IEEE 802.11-99/239. The more comprehensive analysis of this supplement, however, shows the effect of the wider bandwidth to be somewhat more severe than originally predicted by the IEEE-LMSC analysis. Thus, Lucent continues to believe that the proposed WBFH rule changes are contrary to the public interest because any purported benefits of the proposed rules are outweighed by demonstrated costs. As shown in this and our previous filings, WBFH systems will create unacceptable interference to the existing base of FH and direct sequence (DS) spread spectrum products that comply with the current rules. Lucent believes that this increased interference is unnecessary, given the high speed capabilities of existing DS systems. Since WBFH devices will provide functionality no greater than existing DS systems for similar or higher costs and will cause interference to legacy systems, Lucent sees no compelling reason to adopt the proposed FH rule changes.

Sincerely,

Diane Law Hsu

Supplement to the Paper on Interference Potential of Wideband Frequency Hopping

Donald C. Johnson

This is a supplement to the paper *"Interference Potential of WideBand Frequency Hopping Systems on Packet Data Systems"* IEEE p802.11 99/205[2]. A further analysis of the effect of fast frequency hopping is added and the effect of a wider interference bandwidth for a victim receiver is examined. Also, the effect of an unproductive initialization phase (synchronization, start up transients etc.) on hopping segments is added.

It is shown that wideband fast frequency hopping at multiple hops per victim packet has a higher interfering effect on victim systems than when the hop time is limited so that the hop segment and victim packet have the same information content. This latter constraint was the condition analyzed in the original paper.

Section 1 of the reference paper is the abstract. The last two paragraphs of the abstract summarize the numerical results and need a small change due to the new conclusions.[3]

Section 2 of the original paper needs a small change (see next) and section 3 requires no change.

Parameter Definitions

Sections 2 of the reference paper needs only the change described here.

The following parameters were defined in section 2 and some subscripts are changed to achieve better correspondence to the names:

B_v = Bandwidth of the victim system transmitter[4]
B_{vr} = Bandwidth of the victim receiver
B_h = Bandwidth of the wideband frequency hopping (WBFH) system (1, 3 or 5 MHz)
B_{vh} = The interference bandwidth, the difference frequency range over which the WBFH signal interferes with the victim receiver. $B_{vh} >= B_{vr} + B_h$
B_t = Total bandwidth of the WBFH system (75 to 85 MHz.)
H_t = WBFH hop time
P_t = Packet transmission time.

4.0 Composite Interference Effect

This is an amended section 4 of the referenced paper. The section is intended to eventually replace section 4 and footnotes are used to describe the amended sections.

The probability of packet overlap of a wide bandwidth frequency hopping system on a packet data system was developed in section 2 on the assumption of a fixed population of interfering transmitters all of which had sufficient power level to create interference. Section 3 then shows the effect of power level and bandwidth on the size of this population.

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2 This paper is annex 1 of the IEEE 802 LAN/MAN Standards Committee, Second Ex-parte Letter, filed in ET Docket 99-231.

3 The 20 dB number in the next to last paragraph becomes 18 dB and the 13 to 15 dB number in the last paragraph becomes 3 to 20 dB. In the latter case, the 3 dB number reflects slow frequency hopping. Originally only the intermediate frequency hopping numbers were included in the range.

4 In the original paper the parameter B_v was called B_i and B_i was the bandwidth of the interfered (victim) system. The receiver bandwidth and the emission bandwidths were considered to be equal. Here the subscripts v and vr have been adopted and a receiver bandwidth (B_{vr}) is defined that can be different from the transmitter emission bandwidth.

The overall packet interference probability can be considered to be the product of three factors

1. A factor dependent on the hopping frequency or period.
   This is the $(H_t+P_t)/H_t$ term of equation 2-1.

2. A factor dependent on the relative bandwidths.
   This is the $B_{ih}/B_t \approx (B_h+B_{vr})/B_t$ term of equation 2-1.

3. A factor dependent on the interference to victim power level ratio.

Equation 2-1 of section 2 gives the packet overlap probability (λ) dependence on the WBFH frequency hopping rate and bandwidth.

$\lambda = Mp\left[\frac{H_t+P_t}{H_t}\right]\left[\frac{B_{ih}}{B_t}\right]$ and section 3 added the effect of power level.

<u>The Hopping Frequency Factor</u>

This is the factor $\frac{H_t+P_t}{H_t}$ of equation 2-1. This term increases with the hopping rate ($1/H_t$) of the interfering frequency hopper. Increasing the bandwidth as proposed for the WBFH permits the hop time (H_t) to be lowered and thus permits a higher interference factor.

Define the following:

- t_f = the overhead time associated with a packet or frequency hop segment. Assume it is the same for the interfering frequency hopping system and the victim system.
- I_1 = the information content (in bits) of one hop segment.
- I_2 = the information content (in bits) of a victim data system packet.
- S_{ri} = the signaling rate of the interferer system in bits/sec.
- S_{rv} = the signaling rate of the victim system in bits/sec.

The WBFH hop time and the packet transmission time contains a fixed segment and a segment directly proportional to the information content and inversely proportional to the signaling rate. That is

$$H_t = t_f + \frac{I_1}{S_{ri}}$$

$$P_t = t_f + \frac{I_2}{S_{rv}}.$$

The hopping frequency interference factor is then

$\frac{H_t+P_t}{H_t} = \frac{2t_f + I_1/S_{ri} + I_2/S_{rv}}{t_f + I_1/S_{ri}}$, which can also be put in the following form

$$\frac{H_t+P_t}{H_t} = \frac{\frac{2t_f S_{ri}}{I_1} + 1 + \frac{S_{ri}}{S_{rv}}\frac{I_2}{I_1}}{\frac{t_f S_{ri}}{I_1} + 1}.$$

The quantity $\frac{t_f S_{ri}}{I_1}$ is the fraction of the frequency hopper hop time independent of signaling speed divided by that fraction that is dependent on speed. If this is set to a value of f then f is dependent on B_h and I_1 and

$$f(B_h, \frac{I_2}{I_1}) = \frac{t_f S_{ri}}{I_1} = \frac{t_f M_e B_h}{I_1} = \left[\frac{t_f M_e}{I_2}\right]\left[\frac{B_h I_2}{I_1}\right].$$

If the value of f at 5 MHz WBFH bandwidth and $I_2/I_1 = 10$ is taken as f_0 then

$$f(B_h, \frac{I_2}{I_1}) = \frac{f_0}{50}\left[\frac{B_h I_2}{I_1}\right].$$

The constant f_0 is then the ratio of the rate independent to rate dependent hop time at a hopping ratio of 10 and a frequency hopping bandwidth of 5 MHz.

Then

$$\left.\frac{H_t + P_t}{H_t}\right|_{B_h} = \frac{1 + B_h\left(\frac{2f_0}{50} + \frac{M_e}{S_{rv}}\right)\frac{I_2}{I_1}}{1 + \frac{f_0}{50} B_h\left(\frac{I_2}{I_1}\right)}. \qquad \text{4-1}$$

The quantity I_2/I_1 is the ratio of the information content of a victim packet (I_2) to the information content of a frequency hopper segment (I_1), thus this ratio is high if the WBFH system hops at a fast rate compared to the victim packet time.

The ratio of the hopping rate interference factor at the bandwidth B_h to that at the current maximum value of 1 MHz as a function of bandwidth will be denoted F_h. Call the modulation efficiency of the interferer system M_e, that is, $S_{ri} = M_e B_h$. Then the hopping frequency interference factor at 1 MHz is,

$$\left.\frac{H_t + P_t}{H_t}\right|_{1Mhz} = \frac{1 + \left(\frac{2f_0}{50} + \frac{M_e}{S_{rv}}\right)\frac{I_2}{I_1}}{1 + \frac{f_0}{50}\left(\frac{I_2}{I_1}\right)}. \qquad \text{4-2}$$

Taking the ratio of 4-2 to 4-1 gives the relative interference factor for WBFH

$$F_h\left(B_h, \frac{I_2}{I_1}\right) = \left[\frac{1 + B_h\left(\frac{2f_0}{50} + \frac{M_e}{S_{rv}}\right)\frac{I_2}{I_1}}{1 + \left(\frac{2f_0}{50} + \frac{M_e}{S_{rv}}\right)\frac{I_2}{I_1}}\right]\left[\frac{1 + \left(\frac{f_0}{50}\right)\frac{I_2}{I_1}}{1 + B_h\left(\frac{f_0}{50}\right)\frac{I_2}{I_1}}\right] \qquad \text{4-3.}$$

$F_h(B_h, I_2/I_1)$ is the factor by which the mean number of interferers increases when the frequency hopping bandwidth is increased from 1 Mhz to B_h Mhz. The value of F_h will be investigated assuming a fixed value of I_2, the LAN packet information content, and a variable value of I_1. The independent parameter is I_2/I_1 and a large value of the independent parameter corresponds to fast frequency hopping[5].

For high hopping rates, let

$$\left[\frac{2f_0}{50}+\frac{M_e}{S_{rv}}\right]\frac{I_2}{I_1}>>1 \text{ or}$$

$$\frac{I_2}{I_1}>>\frac{S_{rv}}{M_e}\left[\frac{1}{1+\frac{2f_0 M_e}{50S_{rv}}}\right].$$

M_e is the signaling rate for the 1 MHz NBFH {This term is not defined but most likely is Narrow Band Frequency Hopping}system assuming it has the same modulation efficiency as the WBFH system. The limit value of 4-3 under the above condition is

$$\frac{F_h(B_h)}{B_h}\approx\frac{1+\frac{f_0 I_2}{50I_1}}{1+\frac{f_0 B_h I_2}{50I_1}} \text{ (when } \frac{I_2}{I_1}>>\frac{S_{rv}}{M_e}\left[\frac{1}{1+\frac{2f_0 M_e}{50S_{rv}}}\right]) \qquad \text{4-4.}$$

If f_0 is small this is near unity. A large value of the ratio $1_2/I_1$ indicates fast frequency hopping, thus the conclusion:

> *The hopping rate interference factor ratio for WBFH compared to NBFH approaches B_h for fast frequency hopping if the WBFH and the NBFH systems have the same information content per hop and the fixed portion of the hop time is small relative to the modulated part of the hop time.*

Figures 4-1A through 4-1C show the value of F_h/B_h versus the hopping rate parameter I_2/I_1 from equation 4-3 for various typical values of WBFH bandwidth and victim signaling rates. The modulation efficiency is considered to be 2 in these figures, thus the bandwidths of 3 and 5 MHz correspond to WBFH signaling rates of 6 and 10 Mb/a respectively.

The victim signaling rate of 2 Mb/s corresponds to the IEEE 802.11 frequency hopping LAN. The relative interference factor approaches the WBFH bandwidth (B_h) more closely for this low victim signaling rate. The victim signaling rate of 11 Mb/s corresponds to the IEEE 802.11 high rate direct sequence LAN. The relative interference factor is lower for this signaling rate, but is significant even for high values of the f_0 factor.

When $I_2 = I_{1,}$ as in the original paper, f will likely be negligible and

5 In the original version of this paper both the WBFH and victim systems were considered to be packet LANs in which the maximum value of the I_2/I_1 ratio was assumed to be one. That is, the fastest hopping time when both systems are packet data LANs was considered to be the amount of time necessary to transfer one packet of information. This time usually includes an exchange of a long information packet and one or more short supervisory packets. The victim is susceptible to interference on each packet transferred; if either packet is mutilated the information packet will need to be retransmitted.

This expansion of the paper adds the more general treatment of fast frequency hopping.

$$F_h\left(B_h\right) \approx \frac{S_{rv} + M_e B_h}{S_{rv} + M_e} \text{ (if } I_2 = I_1 \text{ and } f \approx 0) \qquad 4\text{-}5.$$

The IEEE p802.11 frequency hopping LAN has an upper signaling speed of 2 MB/s corresponding to an M_e value of 2. Thus it was assumed that $M_e = 2$ in this case and

$$F_h\left(B_h\right) \approx \frac{S_{rv} + 2B_h}{S_{rv} + 2} \text{ (If } I_1 = 1_2, b \approx 0 \text{ and } M_e = 2.)$$[6]

[6] This was the situation analyzed in the reference paper. The more general expression of 4-3 is added by this supplement.

As an example, the relative frequency hopping factor at 5 MHz bandwidth and 11 Mb/s in the original paper was 1.75. Figure 4-1C shows this to be approximately correct for $f_0 <= 0.1$ and the factor is about 1.6 for the highest value of f_0 shown (0.8). The factor is about 2.5 at an I_2/I_1 ratio of about 5 and at the highest f_0 value.

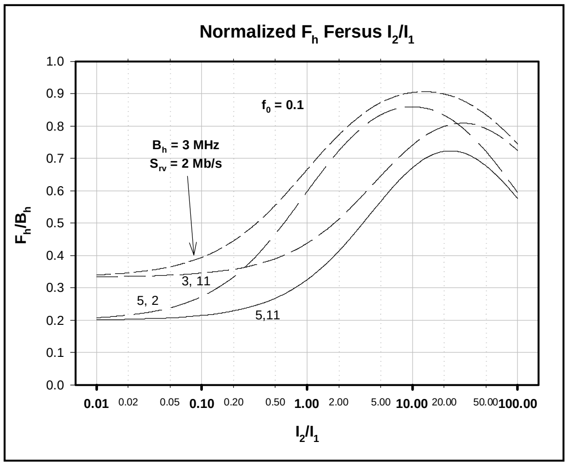

Figure 4-1A

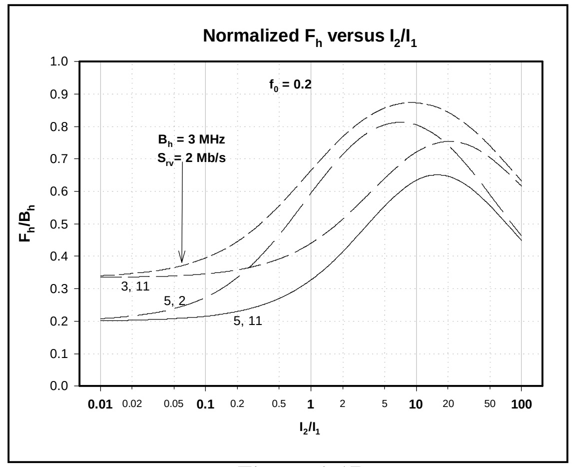

Figure 4-1B

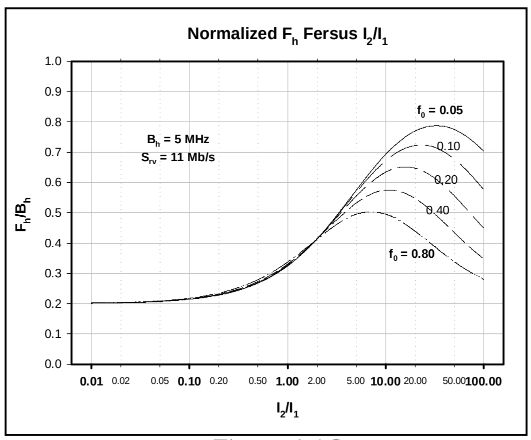

Figure 4-1C

Figure 4-1.
Relative Interference Factor for Fast Frequency Hopping
Versus Hopping Rate Parameter I_2/I_1.

F_h is the ratio of the hopping rate interference factor at frequency hopping bandwidth B_h to that at a bandwidth of 1 MHz.

The hop time consists of a fixed segment not dependent on signaling rate (hardware initialization etc.) and a modulated segment consisting of I_2 bit times. The parameter f_0 is the ratio of the fixed part of the hop segment to the signaling rate dependent part at a 5 MHz WBFH bandwidth (10 Mb/s signaling rate) and an information ratio (I_2/I_1) of 10.

The victim system is a packet data LAN for which the time to transfer an information packet (including supervisory packet transmissions) consists of I_2 bit times at the victim signaling rate. Thus, the abscissa of the figures is a measure of the relative hopping rate. The victim signaling rates of 2 and 11 Mb/s correspond to that of the IEEE p802.11 frequency hopping and high speed direct sequence LANs respectively.

The WBFH modulation efficiency (M_e) = 2 in all figures.

Victim signaling speed S_v (Mb/s)	Frequency hopper bandwidth (B_h in MHz)	Hopping rate factor at I_2/I_1=1 and f_0 = 0.40	Hopping rate factor at I_2/I_1=10 and f_0 = 0.40
any	1	1	1
1	3	2.30	2.53
2	3	1.98	2.46
5.5	3	1.54	2.26
11	3	1.33	2.06
1	5	3.57	3.71
2	5	2.94	3.59
5.5	5	2.07	3.24
11	5	1.65	2.87

Table 4-1: Values of the Hopping Rate Factor

This gives the values of the hopping rate factor for IEEE p802.11 signaling speeds and the proposed WBFH bandwidths. The value of f_0 is 0.40. Figure 4-1 shows the dependence on f_0 and I_2/I_1.[7]

The Hopping Bandwidth Factor

This is the factor $\frac{B_{vh}}{B_t} \approx \frac{B_{vr} + B_h}{B_t}$ of equation 2-1 of the original paper[8].

B_v is the victim emission bandwidth,

$B_{vr} = k_r B_v$ is the victim receiver bandwidth and

B_{vh} is the bandwidth range over which interference occurs.

The current frequency hopping 20 dB emission bandwidth is 1 MHz and the total hopping band (B_t) is proposed to stay the same for the WBFH. Thus, the ratio of the value of this term with a wideband frequency hopping system to the value with a 1 MHz bandwidth frequency hopping system is

$F_b(B_h)$ = Relative bandwidth factor = $F_b\left(B_h\right) \approx \frac{k_r B_v + B_h}{k_r B_v + 1}$.

In the original paper k_r was considered to be = 1. Otherwise this is the same as that of the original paper[9].

Table 4-2 compares this factor for the two bandwidths used in the IEEE p802.11 standard. The frequency hopping PHYsical layer (PHY), 20 MHz bandwidth is 1 MHz and the direct sequence PHY bandwidth is approximately 17 MHz.

[7] The last column is added in this supplement. The value of f_0 was 0 in the third column of the original paper. The corresponding values here do not differ significantly from those of the original paper.

[8] The B_{vr} term was B_i and B_{vh} was B_{ih} in the original paper. The original paper did not distinguish between the emission bandwidth of the victim transmitter and its receiver interference bandwidth. It was detected in some of the responses to the FCC docket that the receiver bandwidth sometimes greatly exceeds the emission bandwidth.

[9] The parameter F_b was not named in the original paper. This quantity was named the “bandwidth factor” in the original paper.

Table 4-2 compares this factor for the two bandwidths used in the IEEE p802.11 standard. The frequency hopping PHYsical layer (PHY), 20 MHz bandwidth is 1 MHz and the direct sequence PHY bandwidth is approximately 17 MHz.

Victim bandwidth (B_i)	Frequency hopping bandwidth (B_h)	Bandwidth factor at $k_r = 1$	Bandwidth factor at $k_r = 1.3$
any	1	1	1
any	1	1	1
1	3	2.00	1.87
1	5	3.00	2.74
17	3	1.11	1.09
17	5	1.22	1.17

Table 4-2: Values of the Bandwidth Factor in Interference Probability
The interference probability of a frequency hopping system is increased by this factor if the frequency hopping bandwidth is increased from 1 MHz to B_h.

5.0 WBFH Interference to IEEE p802.11 Standard LANs[10]

Wireless packet data systems conforming to the IEEE p802.11 standard for wireless LANs will be used as example systems to demonstrate the relative interference potential of wide bandwidth frequency hopping systems. The IEEE p802.11 standard specifies both a frequency hopping and a direct sequence spread spectrum wireless LAN PHYsical layer (PHY) using the 2.4 GHz band. Most systems now in operation follow this standard.

The IEEE direct sequence PHY uses a ***chip rate*** {This term is also not defined and probably should be.}of 11 Mchips/second. The 20 dB bandwidth is not specified but is usually about 17 MHz. The direct sequence signaling speeds are 1, 2, 5.5 and 11 Mb/s. The frequency hopping PHY uses a 20 dB bandwidth of 1 MHz and signaling speeds of 1 and 2 Mb/s.

The IEEE p802.11 wireless LAN products now typically use a power level of about 16 to 20 dBm even though the permissible level is 30 dBm. The lower power level is easier to generate and is sufficient for the inside communication distances for which the LANs are used. The petitioners seeking to increase the frequency hopping bandwidth propose to limit the WBFH power level to 23 and 25 dBm. Since this is above the levels now used, it will likely have little effect on the WBFH power level. It can be expected that WBFH LANs will have about the same power level as current LANs if the power level limit is lowered.

This section evaluates the overall interference effect caused by increasing the frequency hopping bandwidth, taking into account the two factors of section 4 and the power level effect of section 3.

It can be expected that the most severe effect will be on 1 MHz bandwidth frequency hopping systems as opposed to that on the direct sequence systems. This is because the direct sequence systems have higher bandwidth and signaling speed and are more resistant to interference, that is, the interference distance of section 3 is lower.

Direct sequence spread spectrum systems are necessary, within the current rules, if signaling speeds above about 2 Mb/s are required.

Direct sequence systems are very sensitive to fast frequency hopping systems. The IEEE p802.11 standard uses slow frequency hopping which neutralizes the hopping rate factor between the IEEE p802.11 systems and thus makes the standard systems more compatible.

[10] In the original paper, the receiver bandwidth was equal to the emission bandwidth.This section assumes the receiver bandwidth is 1.3 times the emission bandwidth (kr = 3) and fast frequency hopping is added to the tables and examples.

The hopping rate factor of table 4-1 is compared to a 1 MHz bandwidth system that also uses fast frequency hopping. The ratio would be much higher if a fast frequency hopping WBFH system was compared to the slow hopping system of IEEE p802.11.

<u>IEEE p802.11 Frequency Hopping System</u>

Widening the bandwidth without changing the interferer power level reduces the interference power level within a 1 MHz bandwidth frequency hopping receiver, thus β of section 3 is greater than 1 for a 1 MHz bandwidth frequency hopping victim. This power reduction factor (β) for the proposed interfering system bandwidths is

β = 0 dB for the 1 MHz bandwidth,

β = 4.8 dB for the 3 MHz bandwidth and

β = 7 dB for 5 MHz bandwidth.

The IEEE standard frequency hopping LAN C/N requirement is 23 dB for 2 Mb/s and 20 dB for 1 Mb/s and the wide bandwidth signals intercepted by a narrow bandwidth receiver can be treated as gaussian noise. Thus, the C/I (Γ_i of the equations) requirement is approximately the same as the C/N requirement.

The probability of packet overlap is directly proportional to the bandwidth factor of table 4-2 times the hopping rate factor of figure 4-1 and table 4-1. The value of the bandwidth factor (F_b) depends on the ratio of the receiver interference bandwidth to emission bandwidth ratio (k_r). The value of the bandwidth factor at k_r = 1.3 for 3 and 5 MHz bandwidth systems compared to 1 MHz bandwidth systems is 1.87 and 2.74 respectively (table 4-2). The factor due to the hopping rate (Fh) is unity for slow frequency hopping and is on the order of 2.5 and 3.6 respectively for fast frequency hopping (table 4-1).

As an example, assume that the WBFH bandwidth is 5 MHz and the product of these factors is 2.74. This is the minimum value of the factor when the receiver bandwidth factor =3 (k_r=3) and would apply if the WBFH hop time effect was negligible due to a low hopping rate.

Refer to figure 3-3 to assess the power level effect.

For a total area equal to one communication cell (r_t = 1), 85.6 percent of the 1 MHz frequency hoppers will have high enough power level to interfere with the 2 Mb/s IEEE LAN ($\nabla P = 0$, $\beta = 0$ and C/I = 23 dB). 82.5 percent of the 5 MHz frequency hoppers will interfere ($\nabla P = 0$, β = 7 dB and C/I = 23 dB). Thus, the reduction in the proportion that interfere due to the reduced level of intercepted power is 82.5/85.6 = 0.96, provided the systems use the same power level.

However, 2.74 times as many devices of equal power level generate overlapping transmissions when the bandwidth is increased to 5 MHz. The proportion of devices with sufficient power level to interfere would need to be reduced to 1/2.74 to compensate. That is, the proportion interfering would need to be no more than 85.6%/2.74 = 31.2%. This would require an 18.0 dB power reduction in the 5 MHz frequency hopper transmitter relative to the 1 MHz system power level.

If the power level difference is 7 dB (as required by the proposed rules if all systems operate at maximum permissible power), the proportion of interferers becomes 72.6%. Thus, an increase of the bandwidth to 5 MHz accompanied by a 7 dB power reduction increases the number of interferers by at least a factor of 72.6x2.74/85.6 = 2.3.

Table 5-1 shows the result of the above computation for a range of bandwidth and interference factors. The table shows the amount the WBFH power would have to be reduced relative to the 1 MHz bandwidth system power in order to maintain the same interference probability for the 3 and 5 MHz bandwidth systems as for a 1 MHz bandwidth system. The bandwidth-hopping rate factor applies to a 1 MHz bandwidth device with a C/I value of 23 dB. The bandwidth–hopping rate factor (column 3) is shown for slow, intermediate and fast frequency hopping rates. Column 4 gives the parameters defining the hopping rates.

The proportion of devices with sufficient power level to interfere decreases with larger deployment areas. However, even at very large deployment areas the increased bandwidth causes increased interference unless the power level of the WBFH systems is drastically lower than that of the 1 MHz bandwidth systems.

Total radius to cell radius ratio (r_t)	Bandwidth reduction factor β (WBFH bandwidth)	Relative Hopping Rate (I_2/I_1, f_0)	Product of bandwidth and hopping rate factors	Necessary WBFH power reduction (dB)
1.0	4.8 dB (3 MHz)	Slow (<0.1, <0.4)	1.87	18
1.0	"	Intermediate (1, 0.4)	3.70	25
1.0	'	Fast (10, 0.4)	4.60	>26
1.0	7 dB (5 MHz)	Slow (<0.1, <0.4)	2.74	21.5
1.0	"	Intermediate (1, 0.4)	8.05	>24
1.0	"	Fast (10, 0.4)	9.84	>24
1.5	4.8 dB (3 MHz)	Slow (<0.1, <0.4)	1.87	14
1.5	"	Intermediate (1, 0.4)	3.70	20.5
1.5	"	Fast (10, 0.4)	4.60	22.5
1.5	7 dB (5 MHz)	Slow (<0.1, <0.4)	2.74	16
1.5	"	Intermediate (1, 0.4)	8.05	24
1.5	"	Fast (10, 0.4)	9.84	>24
2.0	4.8 dB (3 MHz)	Slow (<0.1, <0.4)	1.87	10.5
2.0	"	Intermediate (1, 0.4)	3.70	17
2.0	"	Fast (10, 0.4)	4.60	19
2.0	7 dB (5 MHz)	Slow (<0.1, <0.4)	2.74	13
2.0	"	Intermediate (1, 0.4)	8.05	21.5
2.0	"	Fast (10, 0.4)	9.84	23

Table 5-1: Necessary Power Level Difference to Equalize Interference Probability to a 1 MHz Bandwidth 2 Mb/s System.

The interference probability of a frequency hopping system of 3 and 5 MHz bandwidth is compared to that of a 1 MHz bandwidth system. The wider bandwidth system power level would need to be less than that of a 1 MHz bandwidth frequency hopping system by the amounts of the table if the interference potential is to be equalized. The victim system has a 1 MHz bandwidth and a 23 dB C/I requirement. These parameters approximately match the IEEE p802.11 2 Mb/s frequency hopping PHY.

Direct Sequence System

The IEEE p802.11 direct sequence PHY uses an 11 Mchip/second signaling rate and has a 20 dB bandwidth of approximately 17 MHz. Thus, the bandwidth factor affecting the number of overlapping transmissions is 1.09 and 1.17 for the 3 MHz and 5 MHz WBFH systems respectively when the receiver bandwidth factor is 1.3 (k_r = 1.3, table 4-2). The hopping rate factor is potentially 1.33 and 1.65 respectively for intermediate rate frequency hopping and 2.06 and 2.87 respectively for fast frequency hopping (table 4-1). Thus, the potential bandwidth – hopping rate factor product is in the range 1.09 to 2.25 for the 3 MHz bandwidth and 1.17 to 3.36 for the 5 MHz bandwidth. Table 5-2 shows the factor values for the typical slow, intermediate and fast frequency hopping case.

A typical 11 Mb/s IEEE p802.11 direct sequence implementation has a C/N requirement of 12.5 dB and a C/I requirement for a single frequency tone of about 7 dB. When a constant amplitude interfering signal has a bandwidth in excess of that of the unspread direct sequence signal, the C/I requirement is higher than for a narrower bandwidth signal. Thus, the C/I requirement for a 1, 3 and 5 MHz bandwidth constant amplitude modulated signal is between 7 dB and 12.5 dB if the interfering signal is of constant amplitude. The requirement increases with increasing bandwidth.

There is no assurance that the WBFH system will use a constant amplitude signal. If the signal is not constant amplitude, the C/I requirement could be as high as the C/N requirement of 12.5 dB.

A C/I requirement of 10 dB will be assumed for comparison purposes. The interference effect would be worse if the WBFH signal is not of constant amplitude.

Table 5-2 shows the shows the amount the WBFH power would have to be reduced relative to that of a direct sequence system power in order to maintain the same interference probability for the 3 and 5 MHz bandwidth systems as for a 1 MHz bandwidth system. The bandwidth-hopping rate factor applies to device such as an IEEE p802.11 standard direct sequence PHYsical layer (PHY) with a bandwidth of 17 MHz, a signaling speed of 11 Mb/s and a C/I requirement of 10 dB.

Total radius to cell radius ratio (r_t)	WBFH Bandwidth B_h	Relative Hopping Rate (I_2/I_1, f_0)	Product of bandwidth and hopping rate factors	Necessary WBFH power reduction (dB)
1.0	3	Slow (<0.1, <0.4)	1.09	3.0
1.0	3	Intermediate (1, 0.4)	1.45	8.5
1.0	3	Fast (10, 0.4)	2.25	14.5
1.0	5	Slow (<0.1, <0.4)	1.17	4.0
1.0	5	Intermediate (1, 0.4)	1.93	12.0
1.0	5	Fast (10, 0.4)	3.36	17.5
1.5	3	Slow (<0.1, <0.4)	1.09	2.0
1.5	3	Intermediate (1, 0.4)	1.45	6.0
1.5	3	Fast (10, 0.4)	2.25	10.5
1.5	5	Slow (<0.1, <0.4)	1.17	3.0
1.5	5	Intermediate (1, 0.4)	1.93	9.5
1.5	5	Fast (10, 0.4)	3.36	14.0
2.0	3	Slow (<0.1, <0.4)	1.09	1.5
2.0	3	Intermediate (1, 0.4)	1.45	4.7
2.0	3	Fast (10, 0.4)	2.25	9.0
2.0	5	Slow (<0.1, <0.4)	1.17	2.3
2.0	5	Intermediate (1, 0.4)	1.93	7.5
2.0	5	Fast (10, 0.4)	3.36	12.0

Table 5-2: Necessary Power Level Difference to Equalize Interference Probability to a Direct Sequence Spread System.

The interference probability of a frequency hopping system of 3 and 5 MHz bandwidth is compared to that of a 1 MHz bandwidth system in which the victim system is a direct sequence spread spectrum system of 17 MHz bandwidth and 11 Mb/s signaling speed. The wide bandwidth frequency hopping system power level would need to be less than that of a 1 MHz bandwidth frequency hopping system by the amounts of the table if the interference potential is to be equalized. The victim system has a 10 dB C/I requirement. These parameters approximately match the IEEE p802.11 11 Mb/s direct sequence PHY.

The table does not take into account the effect of the higher C/I needed for wider bandwidth interferers. This effect is likely on the order of 1 to 3 dB. For example, the overall effect with a 5 MHz bandwidth WBFH system when the deployment area equals the cell size (r_t =1) is 13 to 15 dB for intermediate speed hopping and 18 to 20 dB for fast frequency hopping.

Other direct sequence systems may use lower bandwidth and higher C/I. The effect would be worse on such systems.

An increased bandwidth for a direct sequence system would harm the interference susceptibility from all frequency hopping systems; increasing the direct sequence bandwidth with higher spreading would not be of benefit. This would aid in the relative performance but worsen the overall performance.

Conclusions of Section 5

The specific systems evaluated serve to illustrate the effect of a wider frequency hopping bandwidth on a range of current packet data systems. The effect of increasing the frequency hopping bandwidth is most severe on the 1 MHz bandwidth frequency hopping packed data system because of the low bandwidth and the high C/I ratio. It is less on the direct sequence system because the bandwidth is higher and the C/I is lower for this system.

These specific systems are critical however. IEEE p802.11 has spent 8 years establishing these standards based on the current spread spectrum rules.

6.0 Summary and Conclusions

The effect of the frequency hopping spread spectrum bandwidth and hopping rate on interference generation was first analyzed separately from power level, then the effect of power level was investigated.

A particular physical configuration including a WBFH system and a potential victim system in a common area was analyzed for the influence of power level on interference. The necessary reduction in power level of a wide bandwidth frequency hopping system compared to a system following the current rule in order to maintain equal interference probability was evaluated.

Lowering the regulation limits by 5 to 7 dB for wider bandwidth frequency hopping, as proposed, will not ensure any relative power level reduction on current systems. Current spread spectrum wireless LANs utilize power levels 10 to 13 dB below the allowable limits. This is all that is necessary to operate at the normal inside ranges and propagation conditions now encountered. The regulations would need to lower the limits by at least 10 dB in addition to the values determined here in order to assure the interference potential of the wide bandwidth systems is not higher than that of the current rules.

It was shown that the interference potential increases with the frequency hopping rate as well as bandwidth; and a higher bandwidth permits a faster hopping rate. An upper limit on the frequency hopping rate would be better than a lower limit. The proper upper limit would lower the interference potential of 1 MHz bandwidth systems as well as that of higher bandwidth systems.

Lowering power has little effect on systems with high modulation efficiency. Such systems have a high C/I requirement and the median interference range exceeds most deployment area sizes.

Increasing the frequency hopping bandwidth to 3 or 5 MHz, as proposed, was shown to have a very severe effect on low bandwidth systems with a high C/I requirement such as systems conforming to the current frequency hoping rules. A packet data system conforming to the IEEE p802.11 frequency hopping standard was used as the example of such a system. The necessary power level reduction for this system with slow frequency hopping is on the order of 18 dB compared to a 1 MHz frequency hopping system. It is in excess of 24 dB for intermediate and fast frequency hopping with a 5 MHz WBFH bandwidth.

The effect on a typical direct sequence system was also evaluated. This was shown to be about 3 to 20 dB depending on the hopping rate. Most of this effect occurs with intermediate or fast frequency hopping. The interference effect is benign with slow frequency hopping.

There is a severe effect on direct sequence systems from any fast frequency hopping system, including 1 MHz narrow band systems. The effect is much more severe with wide bandwidth systems. IEEE p802.11 alleviates this effect by requiring slow frequency hopping in the standard frequency hopping PHY.

Interference from any frequency hopping system to a direct sequence system increases with increasing direct sequence bandwidth, even though relative interference of wide bandwidth systems and 1 MHz bandwidth systems decreases with frequency hopping bandwidth. Thus, increasing the spreading gain is not a reasonable option for lowering the interference effect.